

THE RISE OF EXPOSURE ASSESSMENT AMONG THE RISK SCIENCES: An Evaluation Through Case Studies

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Controlling the exposure of human populations to environmental contaminants using a risk-based approach requires both an accurate metric for the impacts of contaminants on human health and a defensible process for selecting which exposures to control. Risk assessment is a process for identifying adverse consequences and their associated probability. The purpose of this article is to provide an overview of the evolving role of exposure assessment in the field of environmental health risk assessment. This overview is provided through a set of case studies, which provide key insight on how exposure assessments are becoming more sophisticated and more important to both the risk assessment and risk management process.

I begin with an overview of the risk assessment process, which includes hazard identification, risk characterization, risk valuation, and risk management. This overview is used to identify the risk sciences and the role of exposure assessment among the risk sciences. I next provide a summary overview of the exposure assessment process and of how it is currently practiced by regulatory agencies and health scientists. Following this is a section that describes the importance of the indoor environment in characterizing and measuring human exposure to toxic substances. I next provide three case studies that illustrate how exposure assessment has been applied in some current environmental health studies and regulations. Although these examples do not capture a full spectrum of the activities going on within the exposure assessment community, they do reveal the interaction of measurement science, theoretical studies, and regulation in the emerging discipline of exposure assessment. These studies include (1) personal air measurements for the total exposure assessment methodology (TEAM) studies, (2) multiple routes of exposure for drinking-water contaminants, and (3) the use of multimedia exposure assessments for assessing the health impacts of contaminated soils. The article ends with a summary discussion of the potential for exposure assessment as a research field.

Presented 4 December 1997; accepted 17 December 1998.

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EXPOSURE ANALYSIS AS A RISK SCIENCE

The U.S. National Research Council (NRC, 1982, 1994) has divided and continues to divide the practice of risk analysis into two substantially different processes: risk characterization and risk management. In addition to risk characterization and risk management, the risk-based approach begins with hazard identification and is motivated by valuation of risk. Risk characterization is the process of both selecting and quantifying the adverse consequences that result from some action (or inaction), such as the use of a chemical such as a pesticide or the use of an industrial process or technology. Risk characterization is used to establish the significance of an estimated risk by defining the magnitude and precision of this estimate. The end product of a risk-based approach to environmental management is either to identify an acceptable level of exposure or to prescribe a required level of technological control. Because it does not involve the direct use of hypotheses formulation and testing but is more related to policy formulation, risk assessment is not considered a formal scientific discipline. Nevertheless, a number of scientific disciplines are involved in the fields of risk assessment and risk management. Because of their importance to the risk field, these sciences have been referred to as the "risk sciences" (Bernard et al., 1995) and include such disciplines as biochemistry, toxicology, epidemiology, molecular biology, exposure analysis, environmental chemistry, pathology, medicine, public health, and statistics/biostatistics.

Human exposures to toxic agents can result from contact with these agents in soil, water, air, and food, as well as from drugs and consumer products. Toxic agents include chemical agents, radioactive materials, and biological agents. In risk assessments, we use human-exposure assessments to translate contaminant sources into quantitative estimates of the amount of contaminant that comes in contact with the human-environment boundaries, that is, the lungs, the gastrointestinal tract, and the skin surface of individuals within a specified population. An assessment of intake requires that we determine how much crosses these boundaries.

IMPORTANCE OF INDOOR AND RESIDENTIAL ENVIRONMENTS

One theme that comes out clearly in the recent literature on exposure assessment is the importance of the indoor environment and residential factors in understanding human exposure to many agents. Recent assessments of the human health impact of airborne pollutants have revealed the importance to cumulative human exposure both of microenvironments such as indoor air and of household sources such as consumer products, combustion, appliances, and tracked-in soil. Efforts to better understand urban air pollutants, such as particulate matter, revealed

instead elevated indoor concentrations of certain pollutants (Melia et al., 1978; Dockery & Spengler, 1981; Spengler et al., 1983). These studies began to focus research on the types, sources, levels, and human health implications of the indoor environment. A number of subsequent studies, most notably the U.S. Environmental Protection Agency (EPA) Total Exposure Assessment Methodology (TEAM) studies, have demonstrated that for a variety of contaminants, residential indoor air is often a more significant source of exposure than outdoor air (Thomas et al., 1993; Wallace, 1993; Pellizzari et al., 1987). Assessment of potential consumer exposures has also been recognized by industry and regulatory agencies as a key part of the overall risk evaluation process for consumer products (Hakkinen et al., 1991).

It is now recognized that there are multiple sources of residential exposures, including consumer products such as cleaners, waxes, paints, pesticides, adhesives, paper products/printing ink, and clothing/furnishings; combustion products from stoves, furnaces, other appliances, and from attached garages; building materials; HVAC (heating, ventilation, air conditioning) systems; personal sources such as tobacco smoke; biological contaminants (e.g., allergens) of human, animal, and plant origin; and outdoor sources of chemicals that infiltrate to the residential environment. The latter include ambient combustion pollutants, contaminated soil particles that can infiltrate or be tracked into the home, drinking water (which can release volatile organic compounds [VOCs] during showering or other use in the home), and contaminated subsurface water (e.g., infiltration of VOCs into basement areas).

The scientific community has been and will continue to be asked to provide measurements and models to address general concerns regarding ambient and indoor air quality. As a result, there is a growing need for technologies to measure personal exposures to a variety of agents associated with public health concerns. These agents include nitrogen dioxide, carbon monoxide, environmental tobacco smoke, volatile organic compounds, ozone, radon, indoor allergens, etc. The recent focus on the importance of childhood exposure has increased the focus on assessing and measuring potential exposures to infants and children in and around the home. Research and development efforts and scientific studies have been undertaken over the past two decades to develop and validate residential monitoring and assessment methods.

EXPOSURE ANALYSIS FRAMEWORK

Exposure assessments contribute to a number of health-related assessments, including risk assessments, status and trends analyses, and epidemiological studies.

Based on the current consensus of the scientific community (NRC, 1991a, 1991b; U.S. EPA, 1992), exposure is defined in terms of contact

with the visible exterior of the person (skin and openings into the body, such as mouth and nostrils). Exposure assessments often rely implicitly on the assumption that exposure can be linked by simple parameters to ambient concentrations in air, water, and soil. However, total exposure assessments that include time and activity patterns and microenvironmental data reveal that an exposure assessment is most valuable when it provides a comprehensive view of exposure pathways and identifies major sources of uncertainty.

In the most general sense, an exposure assessment involves the quantification of a link among a source of contamination, transport, and transformation among a set of environmental media, and human contact with an exposure medium (U.S. EPA, 1989, 1992; McKone & Daniels, 1991). Environmental media include outdoor air, indoor air, ground-surface soil, root-zone soil, plants, groundwater, and surface water in a contaminated landscape, as well as carpets, furniture, and walls in the residential environment. Exposure media include substances with which we have direct contact, such as outdoor air, indoor air, food, household dust, home-grown foods, animal food products, and tap water. Exposure pathways define a link between an environmental medium and an exposure medium. An exposure pathway is the course a chemical, biological, or physical agent takes from a known source to an (often unknown) exposed individual. An exposure pathway describes a unique mechanism by which an individual or population is exposed to chemical, biological, or physical agents at or originating from a source. Each exposure pathway includes a source or release from a source, an exposure point, and an exposure route. Exposure routes are inhalation, ingestion, and dermal uptake.

Because exposure is defined in terms of contact with the visible exterior of the organism (skin, mouth and nostrils), we can view a human, an animal, or a plant as having a hypothetical outer boundary separating internal living tissues from the outside surfaces. Thus, *exposure* is the condition of a chemical contacting the outer boundary of a organism, and exposure over a period of time can be represented by a time-dependent profile of the exposure-medium concentration. *Intake* is the process by which a chemical is physically moved through an opening in the outer boundary of an exposed individual. *Potential dose* is the amount of chemical in the air inhaled, in water or food or ingested, or in a material applied to the skin surface. *Absorbed dose* is the amount of contaminant penetrating the exchange boundaries of an organism after contact. Absorbed dose is calculated from the intake and absorption efficiency. For human populations, it is typically expressed as the mass of contaminant absorbed into the body per unit mass per unit time, such as mg/kg-day.

In the exposure assessment framework for toxic agents, the link among a source, environmental media, and exposure media; the time history of concentration of the agent in an exposure medium; the route of contact (inhalation, ingestion, or dermal contact); and the frequency and

duration of contact are all important components of the quantification of human exposure. For agents with large time variations of exposure concentration, the duration and frequency of contact become very important in defining cumulative contact and potential dose. The duration and frequency of contact depend on activity patterns. An activity pattern is simply a time budget of an individual's activities over some period of time. Activities can be described in terms of an activity type (e.g., recreational, personal care, etc.), temporal variation, and location. Data on activity patterns can be derived from video recordings, from diaries that participants in time-activity surveys complete, or from telephone surveys that request respondents to recall time-activity behaviors.

For many agents that are ubiquitous in several environmental media, total exposure may reflect concurrent contacts with multiple media instead of continuous or multiple contacts with a single medium. Multimedia pollutants give rise to the need to address many types of "multiples" in the quantification of exposure and dose, such as multiple media (air, water, soil); multiple exposure pathways (or scenarios); multiple routes (inhalation, ingestion, dermal); and multiple target tissues for dose and effect.

There are many sources of uncertainty and variability in the process of exposure and human health assessment. Many of these uncertainties and variabilities cannot be reduced. One common approach to addressing uncertainty in exposure and risk assessments is contrary to the accepted principles of decision making under uncertainty. This is the practice of compounding upper bound estimates in order to make decisions based on a highly conservative estimate of exposure. Such compounding of upper bound estimates leaves the decision maker with no flexibility to address margins of error; to consider reducible versus irreducible uncertainty; to separate individual variability from true scientific uncertainty; or to consider benefits, costs, and comparable risks in the decision making process. Because the compounding of conservative estimates does not serve the exposure assessment process well, there has been a growing effort to include sensitivity and uncertainty analyses in the exposure assessment process.

AN OUTLINE HISTORY THROUGH CASE STUDIES

In this section are summaries of three research issues that have had significant impact both for researchers within the exposure assessment community and for regulators who must define strategies for reducing human exposure to toxic agents. Although these cases do not capture a full spectrum of the activities going on within the exposure assessment community, they reveal the interaction of measurement science, theoretical studies, and regulation in the emerging discipline of exposure assessment. Three case studies are discussed. These are (1) personal air mea-

surements for the total exposure assessment methodology (TEAM) studies, (2) multiple routes of exposure for drinking-water contaminants, and (3) the use of multimedia exposure assessments for assessing the health impacts of contaminated soils.

TEAM and PTEAM Studies

Since the early 1980s, the U.S. EPA Office of Research and Development has conducted a series of receptor-based studies on human exposure that make use of personal monitors. These studies, referred to as the Total Exposure Assessment Methodology (TEAM) studies, have demonstrated that for a variety of contaminants, indoor air is often a more significant source of exposure than outdoor air. These studies have dealt with volatile organic compounds (VOCs), carbon monoxide, pesticides, and particles, often comparing indoor and outdoor exposures to these contaminants at the same geographical location and within the same households. In the early studies, exhaled breath and shoulder-mounted monitors were used to measure personal-air exposures to VOCs in the study subjects. Median personal-air concentrations of VOCs were on the order of 2 to 5 times higher than outdoor levels; maximum personal concentrations were roughly 5 to 70 times the highest outdoor levels (Wallace, 1993). These studies revealed the role of various human activities in bringing individuals into contact with chemicals indoors. The studies also revealed the importance of specific sources of exposures that may not be present in residential settings for all individuals. For example, smokers were found to have much higher benzene exposures than nonsmokers, and persons regularly wearing or storing freshly dry-cleaned clothes in their home had significantly higher personal exposures to tetrachloroethylene (Wallace, 1993).

More recently, the U.S. EPA has also funded the particle total exposure assessment studies (PTEAM). PTEAM has focused on measuring personal exposures to inhalable particles (PM_{10}) in the residential environment using specially designed indoor sampling devices (Wallace, 1993). A major finding from this work is that personal exposures to particles in the daytime are 1.5 times greater than either indoor or outdoor concentrations. It has been hypothesized that these data suggest that individuals are exposed to a "personal cloud" of particles due to resuspension of household dust as they go about their daily activities (Wallace, 1993).

Multiple-Route Exposures to Water-Supply Contaminants

For many years, the U.S. EPA and state regulatory agencies considered only the consumption of water and ingestion of fish as pathways for human exposure in the development of drinking-water standards. For contaminated tap water, a contact rate of 2 L tap water per day consumed by a representative 70-kg adult was used to set standards. Because 2 L corresponds to total daily fluid intake by a reference adult and because, on average over a lifetime, most adults only consume only a small frac-

tion of their daily fluid intake directly from the tap, this 2-L contact rate was assumed to be a health conservative value (i.e. plausible but higher than the average value). However, efforts to improve the scientific basis for assessing human exposure to contaminated tap water demonstrated clearly that significant exposures to volatile organic compounds (VOCs) occur from exposure routes other than ingestion.

Based on studies with radon and using experiments in scale-model shower stalls and in actual homes, several investigators have shown that, because VOCs volatilize easily from tap water to indoor air, the inhalation route can contribute significantly to the total body burden of VOCs (Andelman, 1985; McKone, 1987; Nazaroff et al., 1987; Tancrade et al., 1992; Wilkes et al., 1992). These investigations reveal that indoor inhalation exposures to volatile compounds in tap water are comparable to ingestion exposures to a reference 70-kg adult of between 0.8 and 4 L/day (McKone, 1987). An important parameter for assessing the transfer of a chemical from water to air is the transfer efficiency of the VOC from water to air, which has been shown to depend primarily on the diffusion coefficient of VOCs in water (McKone & Knezovich, 1991).

Additional experimental support for the significance of dermal and ingestion exposures to VOCs in tap water can be found in the work of Jo et al. (1990), who measured chloroform levels after 10-min showers in the breath of subjects who showered with water containing dissolved chloroform. The subjects first showered with no clothing and then wore protective rubber suits to eliminate the dermal route. In both cases all subjects had a measurable increase of chloroform in their breath. However, the breath levels dropped by about half when the subjects wore rubber suits, leading Jo et al. to conclude that the chloroform dose from inhalation and dermal uptake were about equal during a shower. Jo et al. (1990) compared these doses to the dose of chloroform from ingestion of 2 L/day of tap water and found that the inhalation and dermal dose were each comparable to roughly 30% of the ingestion dose. Their results imply that the dermal uptake and inhalation intake in the showers each result in an absorbed dose that is equivalent to the amount of chloroform in 0.6 L water. Thus the combined dermal and inhalation absorbed doses are equivalent to the ingestion of an additional 1.2 L/day of chloroform-contaminated water. Using a combination of indoor air and pharmacokinetics models, both Chinnery and Gleason (1993) and McKone (1993) have used an iterative process that begins with model predictions, followed by comparison to data reported by Jo et al. (1990), to reduce the uncertainty in dermal uptake and shower exposure parameters.

Multimedia Exposures to Contaminants in Soil and in Food Chains

Efforts to assess human exposure to contaminants from multiple environmental media have been evolving over the last several decades (Garrels et al., 1975; Mackay, 1979; Thibodeaux, 1979; Bennett, 1981; Ng, 1982;

McKone & Layton, 1986; Allen et al., 1989; McKone & Daniels, 1991; UNSCEAR, 1993; NRC, 1994). Air/soil/vegetation interactions offer complex and scientifically challenging systems that must be understood in order to characterize cumulative exposures for the human population. The need to assess human exposure to global fallout in the 1950s led to an assessment framework that included transport both through and among air, soil, surface water, vegetation, and food chains (Ng, 1982; Whicker & Kirchner, 1987). More recently, reported levels of semivolatile organic compounds (Calamari et al., 1991; Brzuzy & Hites, 1995; Simonich & Hites, 1995) and mercury species (Schroeder et al., 1989) in vegetation and soil at multiple global sites have increased interest in a more quantitative analysis of mass exchange among air, vegetation, and soil.

Contamination in the soil can occur through several different transfer processes—wet and dry deposition of contaminants from air; transfer to soil through the use of contaminated water for irrigating farms, gardens or lawns; and by releases of contaminants inherent to the soil matrix through natural physical or biological processes (Layton et al., 1993). Metal species and radionuclides released from combustion processes or from volcanoes and persistent organochlorine compounds are examples of agents that can be carried globally in the atmosphere (Travis & Hester, 1991; Wania & Mackay, 1995). These releases can result in low levels of soil contamination due to deposition from the atmosphere. Pesticide use and the disposal of radioactive, biological, and chemical wastes, in contrast, can lead to much higher but localized levels of soil contamination (U.S. EPA, 1989). Some natural sources of contamination that are internal to the soil include locally high concentrations of toxic elements (arsenic, lead, etc.), the production of radon in soils, and the replication of toxic organisms.

Human contacts with soil can be multiple and complex (McKone & Daniels, 1991; NRC, 1994). Among the exposure pathways that have received increasing attention are direct soil ingestion, transfer of soil contaminants to vegetation and food products, dermal contact with soil, inhalation of soil particles suspended as dust, and vapor transport into buildings. Exposure issues related to each of these pathways are discussed next.

Direct Soil Ingestion Both adults and children continuously ingest small amounts of soil through inadvertent hand-to-mouth activities. Children who spend a great deal of time outdoors have been observed to contact and ingest soil. Adults are also subject to inadvertent soil ingestion through activities such as gardening, outdoor labor, and cleaning. Several studies have been conducted to characterize soil ingestion by children (see, for example, Calabrese & Stanek, 1991). Some studies make use of soil loading on children's hands in combination with observations of hand-to-mouth activity to estimate soil uptake. Another approach to estimating soil ingestion makes use of tracer elements in feces.

Transfer of Soil Contaminants to Vegetation and Food Products Soil contaminants can be transferred to edible parts of vegetation from the

root zone soil by root uptake and from the surface-soil layer by resuspension/deposition, rain splash, and volatilization followed by partitioning (Jones et al., 1991). Contaminants in the rooting-zone soil are transferred to plant roots from soil gas and soil liquid, with potential transfer in the transpiration stream to above-ground plant parts. Contaminants in the rooting zone can be transferred to surface soil by plowing and tilling or by the activities of burrowing animals such as worms, ants, and rodents. These contaminants can then be transferred to edible plant parts through resuspension/deposition, rainsplash, and volatilization/partitioning. Contaminants in vegetation can be transferred to food products. The level of contamination of vegetative food products often depends on which part of a plant is being consumed. In addition, ingestion by food-producing animals of contaminated soil and soil-contaminated pasture or grains can lead to the contamination of animal-based food products, such as meat, milk, dairy products, and eggs.

Dermal Contact With Soil Dermal exposure to contaminants in soil can occur during a variety of activities, such as construction work, gardening, and outdoor recreation. Adults who work and children who play outdoors can have rather high soil loading on their skin. Lipid-soluble chemicals have a strong tendency to move from a soil layer on the skin surface to the lipid-rich outer layer of human skin. However, the rate at which this transfer takes place is often very slow and could require hours or even days to reach an equilibrium state. Estimating doses that result from contact with a contaminated soil involves a number of often difficult-to-measure parameters, including the contaminant concentration in soil, the soil-to-skin adherence factor, the chemical-specific absorption factor for the skin-soil system, the exposure frequency, and the exposure time.

Inhalation of Soil Particles Suspended as Dust Soil contaminants that are bound to soil particles can be resuspended and inhaled, along with the fine particles to which these contaminants are attached. Inhalation of suspended particles occurs both outdoors and inside buildings. In recent years there has been recognition that a fraction of the fine and coarse particles in the indoor environment originates from outdoor sources. Soil enters the indoor environment by processes such as resuspension, deposition, and soil tracking. Soil tracking is the process by which soil particles are carried into the indoor environment by shoes and clothing of human occupants as well as on the feet and fur of pets. These outdoor sources account for a large fraction of indoor particulates. The remaining fraction of dust-borne contamination is due to indoor sources such as cooking, smoking, carpet wear, and the sloughing of skin cells from humans and pets.

Vapor Transport Into Buildings The vapors of volatile contaminants, such as radon and volatile organic compounds, can be transported into buildings through diffusion from the soil pore spaces. Three principal factors are needed to define the ratio of contaminant concentration in indoor air to observed contaminant concentration in soil gas. These are (1) the

distance between the contaminant source and the building foundation, (2) the permeability of the soil, and (3) the area of cracks in the foundation relative to the total area of the foundation (Johnson & Ettinger, 1991).

SUMMARY AND DISCUSSION

In this overview article, I have provided examples that illustrate the growing importance of exposure as a scientific discipline that supports the process of risk assessment and risk management. One issue that recurs throughout this review is the need to address many types of "multiples" in the quantification of human exposure. We see the need to address multiple environmental media (air, water, soil); multiple exposure pathways (or scenarios); multiple exposure routes (inhalation, ingestion, dermal); multiple chemicals; multiple population subgroups; and multiple health endpoints.

Practitioners of the exposure assessment are now developing measurement and modeling strategies for interpreting from environmental and biomarker measurements the relative contribution of indoor, local, regional, and global sources. In the exposure field, we see a need for exposure models and databases that can address multiple space and time scales. For human populations, total exposure assessments that include time and activity patterns and microenvironmental data reveal that an exposure assessment is most valuable when it provides a comprehensive view of exposure pathways and identifies major sources of uncertainty. In any issue involving uncertainty, it is important to consider a variety of plausible hypotheses about the world; consider a variety of possible strategies for meeting our goals; favor actions that are robust to uncertainties; favor actions that are informative; probe and experiment; monitor results; update assessments and modify policy accordingly; and favor actions that are reversible (Ludwig et al., 1993).

In order to make an exposure assessment consistent with such an approach, it should have both sensitivity and uncertainty analyses incorporated directly into an iterative process by which premises lead to measurements, measurements lead to models, models lead to better premises, and better premises lead to additional but better informed measurements, and so on. In 1996, the U.S. EPA Risk Assessment Forum held a workshop on Monte Carlo Analysis. Among the many useful discussions at this meeting was a call for a "tiered" approach for probabilistic analysis, which is iterative and progressively more complex. The need for formal uncertainty analysis and a tiered approach will require the development by the exposure assessment community of new methods and will put greater demands on the number and types of exposure measurements that must be made.

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